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Introduction to Robotics:
A Soldier's View

Prepared by
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United States Army

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Preface

Just what is a robot? The answer to this important first question requires a look at different definitions. The standard industrial definition of a robot is:

> *A programmable, multi-functional manipulator designed to move material, parts, tools, or other specialized devices through various programmed motions for the performance of a variety of tasks.*

This reflects the likes and interests of its authors. It is relevant to military robots that might be used for industrial-like functions in the support area. It does not address mobile machines that might be used to collect information, disperse smoke, or engage enemy targets on the battlefield. A standard academic definition is:

> *The intelligent connection of perception to action.*

This specifies three required characteristics—sensing, reasoning (the intelligent connection), and action—that must be performed without direct human intervention. From this, we may develop a more broadly applicable definition:

> *Any mechanical system or device that performs a task involving sensing, computation, and action independent of real-time human control.*

Sensors and sensor understanding are critical for initiating and maintaining robot action. Visual sensors with highly developed image understanding abilities are the primary source of environmental information. Tactile sensors dealing with touch and force are also required. A robot must be able to grasp an object with the appropriate amount of force so it neither drops nor crushes the object. Before a robot can act, it must know where it is, where it is going, and how it will get there. In other words, it must have a reasoning and planning ability that can select a good path and execute the motion considering some basic laws of physics. Robots may be implemented on three levels:

- **Explicitly programmed.** Environmental conditions (input) and machine actions (output) are explicitly specified in the program. Any encountered conditions that differ from expected conditions cause failure or are ignored without penalty.

- **Task-Level Programmed.** The machine has a limited ability to respond to environmental conditions that are not explicitly specified in the program. It can also accept limited goal-level instructions and then determine what specific actions are necessary to comply.

- **Autonomous.** The machine has an extensive ability to respond appropriately to novel input; that is, encountered situations or conditions that are not explicitly described in the controlling program. This should not generate any expectations about performance capabilities. Some robots may perform better than humans, some may not perform as well. Also, the set of functional capabilities designed into the robot may be limited; an autonomous robot need not be a universal machine. The key factor is that the machine performs at an acceptable level without scheduled human intervention in the process. What is "acceptable" may vary with the task and domain. For example, the degree of precision required for a material handling task in a factory may be reduced in order to save machine development costs, but still may be acceptable within the overall system. However, the level of precision required in a battlefield mine detection system may be much higher. In this latter case, "close enough" may not be acceptable to users whose lives are at stake.

Generally, current robots have a limited ability to act independently. They usually operate in a fixed position or from a track- or overhead rail-mounted platform. Sensing ability is limited and actions are mostly pre-programmed. Some kinds of robots are very useful in industry and may be adapted to similar Army logistics applications like cargo or ammunition handling. Section I is oriented primarily toward these kinds of robots.

As sensing and reasoning systems become more powerful, autonomous robots—those that operate without direct, continuous human supervision—will be possible. Robot sentries, tactical reconnaissance robots, nuclear/biological/chemical (NBC) reconnaissance robots, decontamination robots, smoke generating robots, and robot weapon systems may be developed when the necessary technological performance level is attained. These kinds of robots are discussed in Section II.

Robots are intended for tasks that generate human fatigue, discomfort, or boredom; robots don't tire, hurt, or daydream. They perform rapidly, consistently, and well in hazardous environments involving things such as high temperatures or toxic agents. They can perform high-risk tasks and potentially can save human lives.

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Section I
Components

Currently, a robot has three component parts: a manipulator, a control system, and a power supply system.

MANIPULATOR

Configurations

The manipulator is the component of the robot that moves and does the work. There are several types of manipulator configurations; the four basic configurations are: *Cartesian, cylindrical, spherical,* and *articulated arm.*

- **Cartesian coordinate**. This type, considered the simplest, consists of straight links (see "Elements" page 3) that move through space along XYZ axes. They are the easiest manipulators to control. A simple drawing is shown at Figure 1.

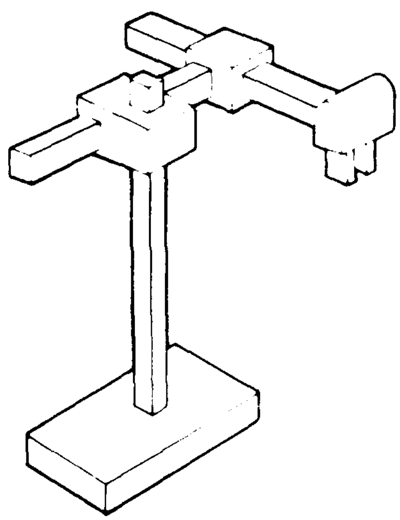

Figure 1. Cartesian Coordinate Manipulator

- **Cylindrical coordinate arm.** In this type, one of the straight-line, horizontal axes of motion is replaced by rotational motion. This allows the robot to work in a cylindrical space rather than one bounded by straight lines. See Figure 2.

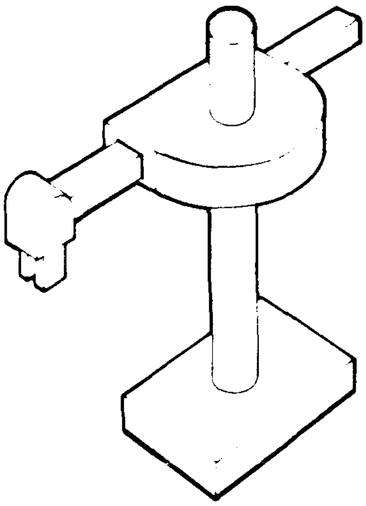

Figure 2. Cylindrical Coordinate Arm

- **Spherical or polar coordinate.** In this configuration, another one of the straight-line axes of motion is replaced by rotation. The manipulator shown in Figure 3 works in a sphere-shaped area, which is a result of the rotating base plus the rotating "elbow."

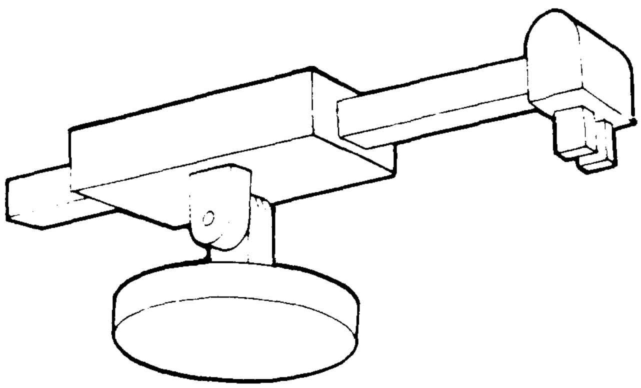

Figure 3. Spherical or Polar Coordinate Manipulator

- **Articulated arm.** One of the most complex configurations is the articulated arm. This configuration is *anthropomorphic*; that is, it attempts to duplicate the configuration of the human arm. This is the most difficult to control, but seems to be of the greatest interest to robotics researchers. It is shown at Figure 4.

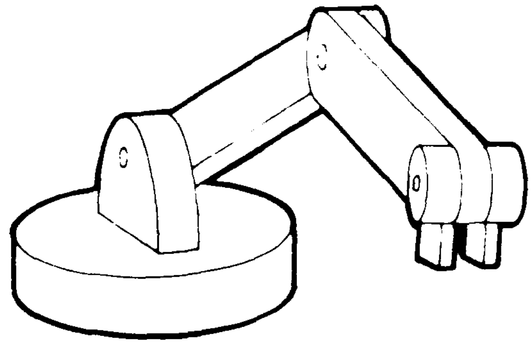

Figure 4. Articulated Arm

This brings up an important issue in robot design. While there is great interest in developing manipulators that work in the same way that human arms do, there is nothing obligatory about the design of the human arm. It may be that the most effective manipulator will be the one that allows a machine to be a machine, not an artificial human. It may be best to design manipulators based on the task to be performed, taking advantage of unique mechanical capabilities without imposing upon the machine the limitations of the human arm. Nevertheless, because of current research interests, anthropomorphic manipulators are the focus of this discussion.

Elements

A manipulator consists of **links, joints**, and an **end effector**. *Links* are the rigid structures that give form to the manipulator. The articulated arm shown at Figure 4 consists of two links. *Joints* are the connectors between links. They are the parts of the manipulator that provide motion. An *end effector* is a particular tool mounted on the end of the arm, such as a grasping device, a paint or decontamination spray gun, or—by extension—some kind of weapon.

The *proximal* joint is the one nearest the manipulator base. The *distal* joint is the one farthest from the base. A cartesian coordinate manipulator includes *prismatic joints*, which slide along a straight-line track. The displacement along this track is called the *joint offset*. An articulated arm includes *revolute joints*, which move in a rotary manner. The displacement in these manipulators is referred to as *joint angles*.

Axes

Manipulators operate with various *degrees of freedom* or *axes of motion*. These terms refer to the directional movement ability of the manipulator. Five degrees of freedom are required for smooth movement from point to point; usually, six degrees of freedom are included as a minimum (the sixth involves rotation). The three major axes are—

- **Vertical Stroke**. Movement of the arm up and down.
- **Horizontal Reach**. Movement of the arm forward and backward.
- **Swing**. Movement of the arm right and left.

The three remaining axes are *pitch, roll,* and *yaw*. These movements are associated with the end effector and provide "fine-tuning" movement. To understand these movements, place your forearm and hand on a table in front of you, fingers pointing straight out to the front. These three axes of motion are—

- **Pitch**. Bending your wrist, raise your hand, keeping it flat with the fingers pointing forward.
- **Roll**. Keeping your wrist stiff, rotate your forearm so your thumb comes up but your little finger remains on the table.
- **Yaw**. Keeping your hand flat on the table, point your hand and fingers to the right.

Robots may have complex manipulators that combine elements and, therefore, combine axes of motion. For example, the Massachusetts Institute of Technology is developing a robotic grasper with three "fingers" and 18 degrees of freedom. The mathematics necessary to control movement of a device like this are extraordinarily complex.

Robots perform their movements within a prescribed *work space* or *work envelope*. This is the area bounded by the points of maximum extension of the manipulator in all directions.

As will be shown later, six degrees of freedom are necessary to specify an object's location and orientation in space. It would seem that a six degree of freedom manipulator is sufficient to reach all points within the work space. This is true, except for the problem of *singularity*. Singularities occur when joints approach the point of maximum extension. Control of the end effector becomes very difficult and, at maximum extension, the end effector may may be unable to reach points that otherwise are within the work space. This can occur in two ways: two or more joint axes may form a straight line and produce *interior singularities*; or, the manipulator may be maximally extended and produce *boundry singularities*. In either case, the manipulator has lost

one or more degree of freedom. Its motion within the workspace will be restricted accordingly. A seven degree of freedom manipulator overcomes the singularity problem; additional degrees of freedom beyond seven show no additional improvement of manipulator control.

Motion

Robot motion may be either *translational* or *rotational*. Translational motion involves movement between points; rotational motion involves movement about a fixed point.

- **Translational.** As a demonstration, recall some of your high school mathematics. On a blank sheet of paper, draw an x-y coordinate plane—a horizontal line (x-axis) crossed by a vertical line (y-axis). Now draw a small square block in the upper right quadrant. Place the lower left corner of the block at the origin—the point where the x- and y-axes intersect—and the bottom edge along the x-axis.

  Now, move the block to the right along the x-axis. Redraw it about two inches to the right, keeping the bottom edge along the x-axis. This is translational motion.

- **Rotational.** Go back to your first drawing. Swing the block up and to the left, keeping the lower left corner at the origin. Redraw the block so that the bottom edge extends to the upper right at a 45-degree angle. This is rotational motion.

Considering this, it is easy to see that within a two-dimensional plane, three types of motion are possible: two of them translational, one rotational. Imagine extending this to three-dimensional space—the domain in which a robot works. In space, six types of motion are possible: three translational and three rotational. Look at your x-y axes again and imagine a third axis vertical to the desk. Imagine that your square is a cube. Three types of translational motion—right-left, forward-back, and up-down—determine its *location* in space. The same three kinds of rotational motion determine its *orientation* in space.

CONTROL SYSTEM

Levels

Robot control systems may be viewed on two levels: a lower level of mechanical devices that constrain movements and an upper level of computers that prescribe movements.

- **Lower level.** The simplest form of robots are called *limited sequence* or *pick-and-place robots*. The end effector repeatedly moves from one specified point to another, sensing only the beginning and end points; there is no concern for the points in between. In these robots, motion is often mechanically controlled by adjusting valves or stops.

  A more flexible control system involves *servo motors*. These are motors that are uniquely suited for robot use because of two characteristics:

  - They include a built-in feedback system, which continuously monitors the position of the motor.
  - The degree of rotation of the motor is directly proportional to the signal input.

  Here is how it works.

  Step 1. The feedback system determines the present position of the axis.

  Step 2. The control system compares this position to a preprogrammed goal position. It determines the difference.

  Step 3. The control system provides the necessary amount of power to the motor to drive it to the goal position.

- **Upper level.** The upper level of control is more complicated. It may be divided into three levels. The first involves *teach* or *guided motion* in which the manipulator is physically manhandled through the motions required to move from a beginning position to a goal position. The manipulator has a learning system that remembers these movements; they are subsequently "hardwired" into the controlling program. A more recently developed level is *explicit programming*. This involves on-line decision making and includes the sensing, planning, feedback, and action expected in robotics. This level depends on a programming language that includes primitive commands allowing the programmer to direct movement between explicitly defined points within the manipulators' work space. The third level—which as yet is just a good idea—is *task level programming*. This approach will allow the programmer to specify high-level actions in terms of the objects and the task goals. The robot will determine the explicit details on its own. Current robot capabilities are limited to explicit programming; task level programming is a research area of considerable interest.

Trajectory

The purpose of control systems is to control motion, or manipulator **trajectory**, which consists of *position, velocity*, and *acceleration*. The relationship is this:

- **Position** is the state of the joint, considering the angle at the joint and the links on either side.

- **Velocity** is the change in position over time. Its two components are speed and direction. Computationally, it is the *first derivative* of position. The term *angular velocity* refers to the speed and direction of joint rotation.

- **Acceleration** is the change in velocity over time. It is the *second derivative* of position.

Kinematics, Dynamics, and Statics

The computations of manipulator motion involve *kinematics, dynamics*, and *statics*. To move a manipulator, the control system must understand the relation of the position of the manipulator and the angles of the joints in the axes of motion. This is *kinematics*. Mathematically, it is not too difficult to determine manipulator position from joint angles. This is *direct kinematics*. It is very much more difficult to determine joint angles from manipulator position; that is, to derive the angles that will produce a desired position. This latter process is called *inverse kinematics*.

Here is another "hand on the table" example. This one demonstrates how motion axes are involved in manipulator movement.

> Sit at a table with your chest close to the front edge.
>
> Place your right hand flat on the table, directly in front of you, close to, and centered on, your chest. Note the angles of your elbow and shoulder.
>
> Without changing your shoulder angle—upper arm and body— move your hand forward. Note that it does not go forward, but rather swings out to the right.
>
> Try it again. This time, it's OK to move your shoulder. Keep your hand flat, do not rotate it in any way, and move it forward. Concentrate on moving the front edge of your hand *straight* forward.

Note that as your hand moves forward, the angle of your elbow increases and the angle of your shoulder decreases. The coordination of these joint movements is easy for humans. It is difficult for machines because of the number and complexity of mathematical computations required for smooth, precise execution of the movement.

However, just deriving the joint angles is not sufficient. The system must determine how much motor torque is required to produce those angles. This is *dynamics*: the relation between axis movement and motor torque. It involves highly complex mathematical formulas that consider gravity, acceleration, velocities, and inertia. Determining trajectory from given motor torques is called *direct dynamics* and is, contrary to kinematics, more computationally complex than *inverse dynamics*, or determining the torques required to produce a desired trajectory.

Manipulators consist of several joints and links. Each link is affected by the others. Computation of forces and torques are inter-related with each other and with the environment. Statics is the relationship between the forces and torques at the manipulator links and the force and torque that the manipulator is exerting on the environment.

The relationship between position of the end effector and the force exerted by it must also must be considered. In many tasks, the force exerted by a manipulator must remain constant as the position changes. Position change, though, alters the amount of force exerted. Combining position control and force control is a problem of *compliant motion.* This is the process by which a person is able to write on a chalkboard—the force of the chalk against the board is kept constant even though the arm goes through some very complex motions. *Guarded motion* is another consideration. As an end effector approaches its goal position, the angular velocity and acceleration of the joints must change significantly. Using the chalkboard example, guarded motion is the process that allows the writer to make contact between the chalk and the board without smashing the chalk.

The mathematical computations associated with all of these relationships consist of complex equations involving matrix algebra and calculus. There is no simple way to deal with this; the next step in the study of robotics is to leap directly into the mathematics.

Feedback Control

Feedback was mentioned earlier as an essential element of servo motors. Feedback is also essential to overall manipulator control, for it is feedback that ensures planned motions are accurately executed in spite

of minute errors that always accompany the computational and mechanical operations of the robot. *Feedback control* consists of measuring the actual motion of the manipulator, comparing that to the planned motion, and modifying the subsequent motion to correct any error. Feedback control ensures accurate trajectories, provides appropriate responses to unexpected obstacles, and regulates forces applied during manipulation.

There are a number of possible sources for error in actual motion:

- Computations are not always precise,
- Kinematic and dynamic models are not always accurate,
- Payloads affect the manipulator differently, and
- Friction and vibration add unplanned disturbances.

Since the resulting errors are not predictable, it is not feasible to include a predetermined correction sequence in the control program. Instead, the program includes a rule for deriving the appropriate correction from a measured error. This is called a *feedback law*. Developing this law is one of the central problems of feedback control. It should consider the history of past errors, but should also be simple enough to operate in real time so manipulator motion is not hindered.

Feedback control is a "fix it once it's broke" approach to the problem of manipulator error. It would be better to prevent the error from occurring in the first place. Such a solution has been developed for the problem of manipulator deflection. Manipulators respond differently to different payloads. The location in space of the end effector may be significantly different for a 150-pound payload from a 25-pound payload. The greater weight will cause a greater degree of deflection—an actual bending of the manipulator—between the joints. For a long time, deflection was corrected through feedback. Recently, a new solution was developed that measures the deflection as it occurs by shining a beam of infrared light from one joint, along the inside of the link, to a matrix receptor at the other joint. This information—where the light shines on the matrix—is then used to compensate for the deflection in the original computations. In this way, deflection is no longer an error requiring correction, it is a characteristic of the manipulator that can be used to the advantage of the overall control system.

POWER SUPPLY SYSTEM

Robots may be driven by **hydraulic, pneumatic**, or **electric** power supply systems. Each has associated characteristics, described on page 10.

Hydraulic

- Can handle the heaviest payloads of all three.
- Requires a "set-up" procedure before operation.
- May have maintenance problems—they can leak!
- Consumes energy when idle as well as when working.

Pneumatic

- Can handle only very light payloads.
- Can produce very rapid cycle rates.

Electric

- Usually quiet operation.
- Consumes less energy than hydraulic units.
- They **don't** leak.
- Limited payloads; requires significant strengthening of the joints as payload increases.

Hydraulic robots currently have a considerable payload-handling advantage. However, advances in electric motor technology have produced motors with reduced size and increased torque ratings. The "payload gap" is greatly diminishing.

Most of the current robots in use share a common problem: the transfer of power from its source to the manipulator joints. This often requires a complicated system of fluid or air lines or perhaps a series of belts and pulleys. *Direct drive* manipulators attempt to overcome this problem by placing the power supply at the joint—the joint itself is an electric motor. Until recently, this meant a considerable reduction in joint strength and precision. However, the recent improvements in electric motor technology have also made direct drive manipulators more feasible.

Other Measures of Effectiveness

- **Payload.** Previously mentioned as an important factor in selecting robot power supply systems, payload is an important consideration when judging the effectiveness of robots as a whole. The ratio between size and weight of the robot and the weight of the payload it can handle is a principal determining factor in selection and design. Other important measures of effectiveness are:

- **Accuracy.** The ability to place the end effector at a specific point upon command.

- **Repeatability.** The ability to return to an initial or previously defined position or location.

- **Velocity.** The maximum speed at which the end effector can move with the manipulator fully extended. (Different from joint velocity.)

- **Reach.** The distance from the base to the farthest point from the base to which the manipulator, with end effector and full payload, can extend.

Section II
Military Robots

Since the Army performs a number of combat support and combat service support tasks that closely parallel industrial tasks, it would seem that there are a great many opportunities for applying robotics. This is only superficially true; the transfer of robotics applications from industry to the Army is hampered by some fundamental differences:

- **Environment.** Industrial robots often have cages around them to prevent accidental injury to humans who might unknowingly enter their workspace. Military forces enjoy no such luxury. Robots must operate in very dirty environments, with widely varying lighting and temperature conditions.

- **Payloads.** Industrial robots are designed and selected to handle specified payloads. This may be possible for Army applications, but military requirements tend to involve much heavier payloads, which either strain capabilities or demand much heavier robots.

- **Uncertainty.** Industrial robots are employed on well-defined, fixed tasks. Military tasks tend to be much more dynamic. Battlefield operations can not be narrowly predicted.

- **Operators.** Industrial users may rely on a workforce of trained operators. While military users may start out this way, personnel demands within a theater may require alterations of the workforce based on factors far more important than machine operator skills. Combat action may make sudden alterations to the workforce.

MAJOR HURDLES

The greatest hurdle involves mobile robots designed to perform combat tasks—robots that will take the fight to the enemy, not just handle supplies in a rear area. Real world military applications for mobile robots make demands that cannot be met by current technology, if the goal is a robot that can move on its own, without human control.

Instructions

The robot must be given mission instructions. The battlefield is no place for a complex computer language. Instructions must be easily issued by anyone, without the need for special, high-level training.

Survivability

Military robots will not be employed in a benign environment. They will be employed in a dynamic, hostile environment where very clever, dedicated humans are deliberately trying to destroy them. They are of no use if they cannot survive long enough to perform their tasks.

Weapons Control

Robot weapons systems can be a great force multiplier if they consistently engage the proper target. They will be of no use if they engage the movement of trees in the wind, a tank that has already been destroyed, wounded or surrendering enemy soldiers who might be a rich source of information, or our own soldiers or weapons systems.

Mobility

A robot must select its own path to a goal location. Generally, this can be done using digitized map data. However, real world movement is dependent upon the conditions of the moment, not maps. Fallen trees, craters, natural terrain characteristics, and manmade obstacles must be overcome. Even if a good path is selected, rain may make it impassable. A robot must have a finely-tuned sense of what it *cannot* do.

Maintenance

Simple problems of either maintenance or environment can cause catastrophic performance failure if a human is not present to apply an equally simple solution. Wiping dust from a lens, clearing a jammed weapon, or pushing the robot out of a rut that was a little too deep are examples. Some of these problems can be designed away but not everything can be anticipated.

Novel Input

The matter of anticipation brings up the most severe problem for autonomous robots. Soldiers survive on the battlefield because they successfully deal with "what happens next," even though that event was not the subject of a specific training experience. Soldiers can adjust to and appropriately respond to novel input. Machines lack this ability. They know what they have been programmed to know and nothing more. When presented input that differs in some way from expected input—a common event on the battlefield—they fail. Their model of the world cannot access the database that soldiers call "common sense."

Solutions

All of this does not mean that battlefield robots are not possible. Indeed, such robots are both possible and feasible, given the right design approach. One way is to severely restrict the operational environment and tasks by limiting the domain and conditions of employment. Rather than trying to model human-equivalent behavior in the natural world, implement a simple computational world model and employ the robot only within those limits. This reduces general utility, but increases the probability of success.

Another approach is to keep people in the loop for difficult or critical decisions. This solves several problems, but adds another big one—communication of visual information between the robot and the remote control station. Hard links, such as fiber optic cables, can be used to provide the necessary rates of data transfer, but they are highly susceptible to disruption by accidental or intentional means. If the link is short and passes through terrain controlled by friendly forces, such links may be appropriate.

Radio frequency links may be used. However, video transmissions require 6 megahertz of bandwidth—for example, every frequency from 90.5 to 96.5 on your FM dial—from an already overloaded frequency spectrum. Microwave transmissions are another possibility, but, again, there is the problem of supply and demand.

Bandwidth requirements can be reduced by a variety of means. One is onboard processing; that is, evaluate data on the robot and transmit only results. This cannot be supported very well by state-of-the-art image analysis programs. Another method is to transmit successive digitized snapshots rather than a continuous video picture. This provides the operator with a somewhat disjointed series of images, but it greatly reduces the bandwidth required. Related to this, only the moving objects—things that change position from one snapshot to the next—might be transmitted, further reducing the amount of data to be transferred. These are all possible. The best, if among them, must be chosen only after considerable field testing.

HIERARCHY OF SYSTEMS

Soldiers will not enter the future with a single leap and find fully-developed robots that think and act as people do. True robots will emerge over time from systems that do not meet the definition specifications, but were developed to apply and exploit interim technical capabilities. While the definition does not include such systems, they must be considered by long-range planners. All of these systems—robotic and otherwise—may be listed in a hierarchy of progressive

intelligence, moving from full human control (dumb machine) to full machine control (intelligent autonomous machine). This hierarchy is described below and shown in the table on the following page.

Human-Operated Systems

This is the baseline. Machines or mechanical devices are tools used by soldiers.

Remotely-Controlled Systems

These systems are still human-operated, but the operator is separated from the machine by a significant distance.

Smart Munitions: Precision Guided Munitions (PGM) or Terminally Guided Weapons (TGW)

These systems are human-operated, but are augmented by a degree of post-launch machine control. In the case of PGM, this is also human-controlled. In TGW, this control is provided by independent means, such as infrared sensors or millimeter wave radars.

Remotely-Directed Systems

These systems include subsystems that may be robotic (explicit or task-level) or otherwise less dependent upon continuous, direct human control. While a human generally directs the machine, individual tasks may be performed under machine control without human intervention.

Hard Automation

These systems operate without direct human control. They perform a single, specific task and are not able to sense or respond to changes in the environment. Examples include a numerically-controlled milling machine and a magazine-type autoloader.

Explicitly-Programmed, Task-Level Programmed, and Autonomous Robots

(Refer to the Preface).

The Hierarchy of Intelligent Machines

System	Class	Characteristics	Advantages	Disadvantages	Examples
Human-operated	Tool	Human operator required. Complete human control.	Highly robust.	Operator required, at risk.	Rifle, tank, aerial bomb.
Remotely-Controlled	Man-Machine	Human operator required, but at location remote from activity location. Complete human control.	Operator removed from risk. One operator, several systems.	Degraded sensing, mobility, overall performance.	'GOLIATH' - WWII German system. (Continuous human supervision).
Smart Munitions	Man-Machine	Human initiated; machine completed. Human and machine share control.	Nonline-of-sight direct fire accuracy for indirect fire weapons.	Probabilistic hits. For TGW, no human terminal control.	Copperhead (PGM). SADARM (TGW).
Remotely-Directed	Man-Machine	Human initiation and intervention. Human control of global tasks; machine control of some local functions.	Reduce operator workload.	Degraded sensing, mobility, overall performance.	Unmanned Aerial Vehicles. (Human supervision; programmed flight control.)
Hard Automation	Automated Device	Human programmed and initiated. Specific, limited, inflexible tasks. Specific work space. Machine control.	Continuous human supervision/operation not required.	Task-specific; inflexible.	Magazine-type autoloader.
Explicitly-Programmed	Robot	Human programmed and initiated. Motions and work space specified. Inflexible machine control.	Manipulation capability without human operator.	Task-specific; inflexible. Complex programming.	Manipulator-type autoloader.
Task-Level Programmed	Robot	Human programmed (global) and initiated. Automatic machine programming for specific tasks. Flexible action within program constraints. Machine control.	Flexibility within defined tasks.	Task-specific. Complex programming.	Not known.
Autonomous	Robot	Human programmed (global) and initiated. Self programming. Flexible responsive to environment. Machine control.	Responds appropriately to environment or situation.	Independent decision ability.	Not yet possible.

SENSORS

Since robots must respond appropriately to the conditions of the moment, they must collect a great deal of information about those conditions. A variety of sensors exists to aid that information collection. Some of these sensors involve rather common techniques; others are at the extreme edge of research.

Image Sensors

Image sensors are connected to some kind of image understanding program—a computer program that analyzes the sensor input and updates the computer database with correct information obtained from the image. In other words, if the sensor acquires the image of a tank, the database is updated with "tank" and not something else. For manipulator tasks in a controlled environment, this is often handled as a matter of *binary images*. The image and its background are presented as areas of "yes/no" light reflectance. For example, a binary image of a full moon against the dark evening sky would show a "yes" reflectance for the moon and a "no" reflectance for the surrounding sky. Image understanding in a natural environment is far more difficult. Outlines are no longer sufficient; the program must consider the surfaces and volumes associated with real world objects. Noise—visual clutter, other objects, and camouflage—must also be considered. As mentioned earlier, current image understanding capabilities do not meet military robot requirements.

Thermal Sensors

People do not depend solely on images to identify objects. There are no reasons why machines should, either. In fact, there are no reasons why machines should be constrained to human-like processes in doing anything. Special sensory abilities of machines may be exploited to produce an object identification capability that exceeds human performance. Thermal sensors offer one such opportunity. A soldier may not see a tank that is carefully concealed in a tree line, but a thermal sensor can easily pick out the tank from the heat signature of its engine. Beyond this, a thermal sensor can also identify the ambient thermal characteristics of the steel tank body, which differ from those of the surrounding vegetation.

Laser Sensors

Laser sensors can determine depth in an image. Given a two-dimensional image of a natural scene, it is very difficult to determine which objects are in front of the others and how far the objects are apart. Laser imaging devices are able to break down an image by range, thereby determining the third dimension in the scene.

Audio and Seismic Sensors

Audio sensors not only pick up the sounds of vehicles, but also differentiate between sounds that exhibit vehicle-unique characteristics. Seismic sensors can pick up signals of cross-country movement and can be gaged to operate within given ranges, such as tanks, trucks over 5-ton class, and so on. These sensors, and those described above, provide additional cues in identifying objects in extremely complex domains. Individually, they all have weaknesses; combinatorially, they have great strength.

Other Sensors

Other sensors are needed for operational tasks. A variety of common sensors monitor the status of vehicle components. *Tactile sensors* are needed to determine contact with other objects and may help solve one of the problems of off-road trafficability: how firm is the surface? Will it support the robot? Other sensors have yet to be invented. As we move closer to autonomous robots, we will kn v better what kinds of information are essential for operation. New sensors will probably be required to meet new needs.

APPLICATION ISSUES

Mobility

- **Obstacle Avoidance.** One of the capabilities most needed by military robots is mobility. Walking into a restaurant and tak'ng a seat at a table is a simple task for humans; it is a very hard task for robots. The problem involves obstacle avoidance. It requires *spatial reasoning* that will enable a manipulator to move through a cluttered work space or a mobile robot to move through a cluttered room or across open terrain.

  One way of planning a path around obstacles involves the *configuration-space transformation*. The process solves the hard problem of moving an object through space by transforming it into an easier problem of moving a single point through space. This technique was developed for manipulator control, not terrain-traversing robots, but the potential for application exists. A robot may collect environmental information through its sensors and then apply the configuration-space transformation to select a clear path. Since new information is collected as the robot moves, this is a continuous process.

  A more useful method for solving the robot mobility problem involves three levels of analysis that address the three levels of the problem: *planner, navigator,* and *pilot*. Consider a short

automobile trip as an example. Suppose you want to go to your local computer store for an additional box of disks. The first step is to determine a good path from your present location to the store. This is the role of the *planner.* The result might be a list of instructions, such as—

> Go down Elm Street to 24th Street
> Turn left on 24th Street
> Go down 24th Street to Pittsburgh Avenue
> Turn right on Pittsburgh Avenue
> Stop at 121 E. Pittsburgh Avenue

But this is just a plan. You must have the ability to execute the plan on the ground. This is the function of the *navigator.* The result is to control movement of the automobile in a way that matches the instructions of the planner. Roads and landmarks must be identified; correct turns must be made.

This, too, is not sufficient. As you travel, you will encounter things that were not in the instructions and that are not on any map. You must obey changing traffic signals, you must stop for the child who chases a ball into the street in front of your car, and you must drive around the enormous pothole on Pittsburgh Avenue. This is accomplished by the *pilot*—execution of the instructions considering the environmental conditions of the path at the time of execution.

This sequence of planner-navigator-pilot may be applied to mobile robots. The planner program may chose a good path from map data. This is not a particularly difficult task. The navigator program must guide the robot across natural terrain according to the plan. This is a difficult task because it requires a degree of machine-based image understanding that goes beyond the current state of the art. Lastly, the pilot program must respond to unexpected situations and obstacles along the path. This is extremely difficult because it requires real time spatial reasoning, real time three-dimensional path planning, and that elusive common sense mentioned earlier. It is good if the robot avoids running into a tree that has fallen over the road. It is not good if the robot drives into a river simply because the path to the river edge was less cluttered than the path to the bridge.

- **Legged Locomotion.** Almost all of the mobile robots being developed in research laboratories use tracks or wheels as a means of locomotion. Wheels are cheap, easy to maintain, and may be powered very precisely. Tracks provide a better ability for overcoming obstacles and are the object of a long-standing

love affair by a large part of the Army. Very few researchers, and even fewer military planners, are considering legs for robot mobility. This is unfortunate, for something like 60% of the earth's land surface is not navigable by current wheeled and tracked military vehicles. Legged vehicles show great potential for moving across extremely irregular or rugged terrain, negotiating steep inclines, and overcoming high obstacles. They could ford streams, cross cratered areas, and even climb stairs. Legged locomotion shows great potential for application to mobility in natural environments.

"Potential" is the key word. No practical walking robot has yet been developed. Demonstration systems have been built that exhibit precise control and favorable payload-to-weight ratios, but they move very slowly. The problem is one of stability. Current legged robots operate under *static stability*; that is, they move in a series of stable positions—from one to another—rather like a human moving one step at a time. But, as humans found out long ago, this is not a particularly effective means of movement. Humans developed the ability to move under dynamic stability. This is basically a state of constant instability made stable by the movement. Walking is really a controlled fall. We shift our center of body mass forward until we become unstable, then we move our foot forward to prevent a fall. Doing this rapidly in succession creates movement that is continuously unstable; disaster is averted by continuous muscle control. Legged robots must be able to move under dynamic stability, as people do. Only this provides the speed and flexibility required by operations in a natural environment. Unfortunately, dynamic stability is still a matter of research.

World Model Representation

Mobility is one of two major control problems associated with military robots. The other deals with the robot's actions: how does it know what to do and when to do it? The common ground of these two issues is the world model, or the representation of the real world in computer memory. Autonomous robots must "know" a lot about the real world if they are to interact with it effectively. Their model of the world must provide environmental information that explains roads, swamps, potholes, rivers, mud, ice, gravity, daylight—a wealth of practical information that humans take for granted. Their model must also provide procedural information that addresses general subjects such as the relation between speed, inclines, turns, and stability as well as mission-specific subjects such as the relation between being observed by an enemy and survivability.

This is probably the fundamental problem facing developers of military robots. If this problem can be solved, many of the other problems become a matter of engineering. This problem is recognized by researchers as particularly difficult, not because the solution is hard, but because the solution method is unknown. Artificial intelligence researchers have made several promising starts using sets of rules, networks, hierarchies of clumps of information, and various logic-based systems. All show some deficiency; all are incomplete.

Power Sources

Mobile robots may be powered by a variety of sources. Gasoline or diesel engines are an obvious choice for large robots, but not a good choice for small systems where the fuel storage requirement or noise signature might present a mission-limiting problem. Electric power is an obvious choice for small robots. Storage batteries are becoming smaller, lighter, and more powerful, but there is still a time limit on their use. Solar receptors can provide a limited source of electricity. A hybrid engine, which combines diesel and electric power, is a good solution for some small robots. The diesel engine, with a small fuel tank, can provide power for cross-country movement. Once the robot is in place, it can switch to battery power for more silent operation. It can "go to sleep"—terminate most functions and conserve power—until "awakened" by command or an onboard sensor alarm, at which time it brings all functions back on line. It might stay in low-power mode for many hours, then start its engine for a brief recharging session. Many options are possible. They must be considered along with the application to best match the power source and its intended use.

Problem Avoidance

All of the difficulties described above indicate that robots will not be fully developed for some time. They do not indicate that we can or should do nothing until they are all overcome. The easiest way to develop an early system in spite of technical limitations is to limit application to avoid the shortcoming. If cross-country mobility is a severe technical problem, then don't require it. Intelligent machines may be developed that are stationary, but still contribute to improved effectiveness and efficiency, particularly in the logistics domain. Whether such a machine is a robot or not is functionally immaterial. If it is a tool that helps a soldier do a job, it is useful. If a collection of these tools help the Army succeed, that is all that matters.

POTENTIAL APPLICATIONS/NEW CONCEPTS

Generally, military applications of robotics may allow the use of machines—

- Where we cannot or would rather not use people.
- To improve the level of task performance.
- To reduce the number of people required to perform a task.
- To enable new, previously impossible, operational concepts.

More specifically, robots may be applied to a wide variety of battlefield tasks such as:

- Unmanned mobile/stationary ground systems that employ a variety of sensors to the front, flanks, or rear of maneuver forces. These may be used for reconnaissance, surveillance, target acquisition, or fire control.
- Unmanned anti-armor systems that may be employed by ground forces to engage attacking enemy formations before the defenders are within range of the attacker.
- Autoloading and munitions management systems for direct and indirect fire weapons.
- Systems for rearming and refueling tactical vehicles in forward areas.
- Systems for investigating, identifying, monitoring, and rendering safe unexploded ordnance.
- Systems for reducing or clearing complex obstacles under fire, immediately forward of advancing heavy forces.
- Systems that will deceive the enemy as to the true friendly strength, disposition, composition, or intention.
- Systems for decontaminating vehicles, equipment, and clothing.
- Systems to support automated materials handling and warehousing operations at fixed or hasty locations.

The tasks described above are probably all possible given enough time and money. They are all examples of doing a current task better. The real promise of military robotics may be in new concepts—things that were impossible before, things that were never thought of because a certain capability never existed. Such things are not listed here or anywhere else. They are locked up in the imaginations of soldiers.

Section III

Conclusion

This brief tutorial scratches the surface of robotics. It provides the basic vocabulary and concepts that allow informed investigation and discourse as well as additional study of more specific technical aspects. Further study may be appropriate for some readers. Successful application development of military robotics depends upon two kinds of expertise: expert knowledge of the application domain—Army battlefield operations and tactics—and expert knowledge of the technology to be applied.

One of the lessons learned during combat operations in the Persian Gulf must surely be that high technology works! Because of costs and other risks, it must be approached prudently and applied wisely, but it works—it is nothing to be avoided.

Technology is always advancing; there are always new challenges and new opportunities. The men and women who carry the obligations of defense know perhaps better than others that tomorrow belongs to those who best prepare for it. Technology exploitation is an essential part of that preparedness. Nothing less than our national well-being depends on it.

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